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An integrated pest management program for burrowing shrimp control in oyster aquaculture

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Abstract

Integrated pest management is widely applied in terrestrial agriculture, but less so in aquaculture. Parallels to insect control in agricultural fields were exploited in this application of integrated pest management principles to control burrowing shrimp *Neotrypaea californiensis* and *Upogebia pugettensis* in Pacific Northwest U.S.A. oyster aquaculture. The pesticide carbaryl has been applied to oyster aquaculture tracts to control burrowing shrimp in Washington state coastal estuaries for over 40 years. Infestations of these shrimp reduce the stability of the bottom substrate where oysters are raised and cause them to be covered with sediment and die. The use of carbaryl to control these shrimp continues to receive scrutiny despite substantial evidence that there are few if any long term environmental impacts, and the industry recently agreed to limit this practice and implement integrated pest management. The efficacy of the current control program was investigated and a monitoring plan which achieves level 1 goals of an integrated pest management program is described. While the pesticide was found to be 84–96% effective at removing shrimp from a given bed, new individuals can recruit back to these beds as post-larvae on an annual basis. Shrimp recruitment was low during the years of this study (1999–2002), and most monitored beds remained relatively shrimp free after treatment compared to previous records from the early 1990's when shrimp recruited more frequently and higher burrow densities were recorded on oyster beds. Some monitored beds were re-treated with pesticide during this study under the guidelines of the current pesticide application program (threshold of 10 shrimp burrows m^{-2}). An attempt to experimentally define a true injury threshold as the basis of an economic action threshold for pesticide treatment, indicated that shrimp cause substantial oyster losses at levels exceeding 20 to 40 shrimp burrows m^{-2}. Further refinements seem unlikely given the perennial nature of this crop and a multitude of market and environmental variables affecting both crop and pest. Instead, we propose the use of an empirical decision tree in conjunction with a shrimp monitoring program to implement integrated pest management, regardless of whether the pesticide or alternative control measures are chosen as the final tool(s) for shrimp control.
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1. Introduction

Two species of indigenous burrowing thalassinid shrimp have posed a serious threat to the oyster aquaculture industry in estuaries along the west coast

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of North America since they were anecdotally reported to increase in the 1940's. These shrimp soften the intertidal substrate where oysters (*Crassostrea gigas*) are raised and cause them to be covered with sediment and die (Feldman et al., 2000; Dumbauld et al., 1997). Oyster aquaculture is a multi-million dollar industry in Washington state which leads the U.S.A. in farmed shellfish production and Willapa Bay alone produces over 10% of the country's oysters (Ruesink et al., 2006). Both ghost shrimp (*Neotrypaea californiensis*) and mud shrimp (*Upogebia pugettensis*) reside in burrows that can extend up to a meter below the sediment surface (Dumbauld et al., 1996; Bird, 1982; MacGinitie, 1930, 1934; Stevens, 1928). Feeding and burrowing activity by thalassinid shrimp have been shown to affect bivalve shellfish near the surface, but also to alter the structure of benthic infaunal communities either directly by decreasing the number of non-burrowing sedentary filter feeders present or indirectly by influencing the presence of seagrass in these estuaries and several other locations around the world (Dumbauld and Escheverria, 2003; Tamaki, 1994; Posey et al., 1991; Tamaki, 1988; Posey, 1986; Suchanek, 1983; Peterson, 1977).

After several years of research by scientists and other agency personnel (Washington Department of Fish and Wildlife;WDFW, 1970), the oyster aquaculture industry in Washington state, U.S.A. discovered a solution to the problem in the early 1960's, when they adopted a treatment program utilizing the pesticide carbaryl (1 napthyl-*n*-methyl carbamate, brand name Sevin 80SP®, Feldman et al., 2000; WDFW and Washington Department of Ecology,WDOE, 1985, 1992). Carbaryl is a relatively broad spectrum pesticide that was widely used in terrestrial agriculture and was chosen due to its efficacy, low mammalian toxicity, lack of response and little uptake by oysters themselves (WDFW, 1970), and rapid hydrolysis and breakdown with no bio-accumulation in non-target organisms (Mount and Oehme, 1981; Cranmer, 1986). The active ingredient inhibits acetyl-cholinesterase activity at the nerve synapse in arthropods and it is applied directly to the intertidal substrate at low tide to kill burrowing shrimp. The pesticide application program was successful, but unique because it occurred in a water body where efforts were being made to reduce the amount and impact of pesticides coming from terrestrial sources. Consequently the practice has raised environmental concerns since its inception. This was especially the case during the mid 1980's when carbaryl use for shrimp control was banned in Oregon and California (Bakalian, 1985; Buchanan et al., 1985) and an environmental impact statement (EIS) process was initiated in Washington (WDFW and WDOE, 1992).

Evidence suggested that oysters could not be farmed at any appreciable scale in Willapa Bay and Grays Harbor without some form of shrimp control, so integrated pest management (IPM) was chosen as the preferred alternative in the EIS in an attempt to improve control measures and minimize potential environmental impacts. While the carbaryl spray program continued, two committees were formed in an effort to understand and implement IPM (Eng, 1996; BSC, 1992). It became apparent during this process that there were substantial differences between IPM applied in terrestrial agriculture and that used to control these crustacean pests in the marine aquatic environment. In a review of the program, DeWitt et al. (1997) cited five critical needs which they felt necessary to address before a true integrated pest management plan could be implemented. Although the search for other control methods to integrate with pesticide use continues, three of those needs are pertinent to this study which was designed to strengthen the monitoring program:

1) Development of accurate shrimp population census methods. A monitoring program which produces density estimates for pest populations is fundamental to all aspects of an IPM plan. The existing practice of using burrow counts taken in early spring (March–May) was deemed to provide poor estimates of the shrimp populations.
2) Characterization of a damage/density function. Knowledge of the quantitative relationship between pest density and crop damage is also a critical element of IPM. The existing regulatory criterion of 10 shrimp burrows m^{-2} was not based on a scientific assessment (WDFW and WDOE, 1985).
3) Development of objective decision-making criteria for use of control tactics. A fundamentally new economic injury level model needed to be developed based on the damage density function in #2 above.

In January 2001, the growers, several state agencies and other parties signed a memorandum of agreement to transition the industry towards integrated pest management. The study we report on here was associated with that effort and had four objectives: 1) Estimate observer error and quantify efficacy of the current burrowing shrimp control program on commercially cultivated oyster beds by making these measurements just before and 1 month after pesticide application, 2) Follow patterns of shrimp recruitment and survival and compare these with oyster survival and production as well as eelgrass and algal cover as other important environmental characteristics over a typical grow-out cycle on these cultivated beds 3) Attempt to experimentally define the damage density "threshold" concept noted above and 4) Use the data to develop and implement an efficient long term monitoring program. These objectives address the critical needs outlined above and form the basis for Level 1 IPM integration which include an accurate monitoring program with field scouting of pests and threshold levels for treatment and inaction (Kogan, 1998).

2. Materials and methods

2.1. Research sites

This study was carried out in Grays Harbor (46°55′N, 124°08′W) and Willapa Bay (46°40′N, 124°0′W), Washington, U.S.A. These estuaries have broad shallow intertidal mudflats which are greatly influenced by both large semidiurnal tides and relatively strong wind forcing, small riverine influence especially during the summer months (average daily salinity ranging from 20 to 30 ppt), and are therefore well mixed and heavily influenced by the nearshore coastal ocean (Banas et al., 2004; Hickey and Banas, 2003; Ruesink et al., 2003) Approximately 40 individual shellfish tracts are chemically treated for burrowing shrimp each year in these two estuaries combined, representing an average of 684 acres from 1994–2004 with an 800 acre annual limit imposed after the 1992 supplemental EIS. We chose 13 of these tracts to sample in 1999 subject to availability, with the goal of sampling at least one tract in each major geographical area used for oyster culture in each estuary (Fig. 1). Ten of these beds were monitored for three years (1999–2001) to complete an oyster grow-out cycle and five of these beds continued to be monitored each year through 2004 (5 years). Eight additional beds, again selected across a geographical gradient in both estuaries, were sampled in 2000 for which we present data on pesticide efficacy only.

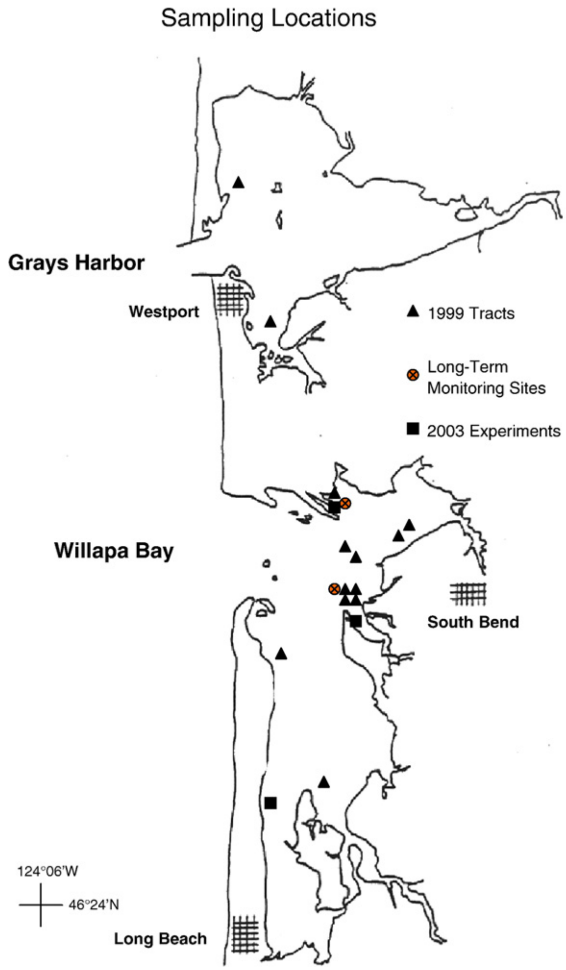

Fig. 1. Map of Willapa Bay and Grays Harbor showing location of oyster tracts that were monitored in 1999 (triangles), a subset of which were monitored for 3–5 years thereafter. Also shown are the locations of two long term monitoring sites in Willapa Bay where shrimp recruitment and adult shrimp populations have been monitored since 1992, and the location of small plots and the large scale threshold experiment conducted in 2002–3.

2.2. Program efficacy

Efficacy of the conventional carbaryl-based pesticide management program was assessed by counting shrimp burrows on each of the 13 tracts chosen in 1999 and 8 additional tracts in 2000 just before (early July) and approximately 1 month after pesticide application (after shrimp died and their burrows collapsed, Dumbauld et al., 1997). Although shrimp burrow counts have previously been noted to be highly variable on both spatial and temporal scales (DeWitt et al., 1997; Dumbauld et al., 1996), we used burrow count measurements taken on the surface as our primary tool to assess shrimp density in this study because sampling shrimp directly with cores would be impractical at the broad scale necessary for a full scale monitoring program. A transect that bisected each tract was chosen and sampled using a 1 m^2 quadrat placed on the substrate at 20 regular systematic intervals with a random starting point (distance between observations varied depending on bed size). Pilot survey work (Dumbauld, unpublished) suggested that although a systematic survey design produced less precise results than a stratified random design, both resulted in substantial improvements (half width of the 95% confidence interval with 90% probability dropped below 30 burrows m^{-2}) when a sample size of 20 was reached. Practical time constraints due to the tide (1–4 hour sampling window each day), precluded using the stratified random design and also limited the number of observations on a given bed to approximately 20 samples. Visual assessments of shrimp burrow count (# 0.25 m^{-2}), oysters present (% shell cover m^{-2} and # oyster cultch shells with small oyster spat and later counts of resulting clusters of oysters), eelgrass turion (=stem) count, and macro-algae (% cover) were made in each quadrat. Burrows were generally counted in a 0.25 m^2 area within each quadrat when abundant. Sample size was re-assessed using pre-treatment data and observer error was quantified in 1999 with burrow counts made by two individual observers on a subset of the tracts.

2.3. Long term monitoring of shrimp/oyster dynamics

Shrimp and oyster populations on oyster tracts were monitored over a 3 year oyster crop grow-out cycle by conducting annual systematic transect surveys on each of 10 tracts for which efficacy monitoring began in 1999. Sampling occurred in late July at approximately 1 year intervals after treatment from 2000–2002. Data collected included shrimp burrow count (# 0.25 m^{-2}), oysters present (% shell cover m^{-2} on the surface and # oyster cultch shells with spat and later resulting clusters of oysters), oyster size (2 oyster clusters each resulting from one piece of cultch with spat were collected from every other sampling point and all individual oysters measured in the laboratory), eelgrass (turion count, # m^{-2}) and macro-algae (% cover m^{-2}). In three cases, beds that had been treated in 1999 were re-treated within this sampling interval, in which case assessments were made again before and after treatment during the second treatment year. Burrow count data were also compared to those collected by a contractor whom the growers retain each year to complete pre-season pest assessments for the state management agency (Washington Department of Ecology, WDOE). These counts are typically made from early April through June using a 0.25 m^2 quadrat (10–20 per tract), but at least at the outset of this study, not following a standard spatially explicit sampling design. We accompanied the contractor to 6 sites in Willapa Bay in 2004 and collected side by side count measurements.

In addition to counting shrimp burrow openings on the 10 oyster tracts selected for long term monitoring, recruitment of juvenile shrimp to these locations was assessed in 2000 and 2001 using sediment cores (26.5 cm diameter × 15 cm depth) and sieving contents through 1 mm mesh. Ten samples were taken along the same transect bisecting each tract (systematic sample with a random starting point) in early spring (March–April) for ghost shrimp (recruitment typically occurs in August–November, Dumbauld et al., 1996) and in July for mud shrimp (recruitment typically occurs from April–June,). Additional samples were taken in September at previously established control sites of particularly high shrimp density as part of a long term monitoring program for shrimp recruitment in Willapa Bay (haphazard samples taken within a shrimp colony). Samples were taken in September with the same size core, but a finer mesh sieve (0.5 mm) used for very recent ghost shrimp juveniles and a larger core and sieve for all sizes of mud shrimp (40 cm diameter × 60 cm depth, 3 mm sieve), since these shrimp have grown substantially by September. Adult populations of ghost shrimp were monitored separately using this larger core.

2.4. Injury threshold experiments

Experiments to investigate whether an injury threshold could be defined were initiated in May 2002. Sixty pieces of oyster seed (small juveniles or spat on oyster shell cultch) were placed on each of 12 small (2 m × 2 m) plots established at a location near the Cedar River long term monitoring site in Willapa Bay (Fig. 1). Four plots were placed in an area with very high ghost shrimp density (>90 burrows m^{-2}) and four in an area of moderate density (20–35 burrows m^{-2}). Each plot was surrounded with short (20 cm high) plastic fencing to prevent shell loss due to physical weather effects. The number of shrimp burrows in each of four 0.25 m^2 sub-plots was recorded, along with the number of oyster seed, eelgrass turions, and percent algal cover measured at periodic intervals over 4 months.

A second set of plots was established in summer 2003 on four different oyster beds with generally lower shrimp abundance (two at this Cedar River location, one nearby but across the channel and one near the south end of the bay near Nahcotta, Fig. 1; 2002–3 experiments). Sixty pieces of oyster seed were again enclosed within each of several small (2 m × 2 m) plots of differing shrimp burrow density (<10 to >40 burrows m^{-2}) using plastic fencing to prevent seed loss. Results were compared with several unfenced areas which were established to determine fence effects. The number of shrimp burrows in each of four 0.25 m^2 sub-plots was recorded, along with the number of oyster seed in each plot during several subsequent tidal series.

Finally, a 135 m × 45 m (1.4 acre) plot was marked out on a commercial oyster bed that was heavily infested with burrowing shrimp (ghost shrimp) near Goose Pt. in Willapa Bay (Fig. 1; 2002–3 experiments). Half of the plot was aerially treated with carbaryl in June 2003 while the other half remained untreated. In August, after the treated substrate had become suitably firm, the upper halves of both treated and untreated plots were planted with oyster seed at a commercial density by the bed owner, while medium sized ("fattening") oysters were moved onto the lower halves. Shrimp burrows and oysters were counted within each of 20 or more 1 m^2 plots aligned along two intersecting diagonal transects in each plot before and periodically after shell placement. Oyster density was measured as both seed count and as percent shell cover.

2.5. Grower interviews

Six growers whose beds we collected data from were interviewed in 2004 to corroborate the data on bed use and oyster production and to assess grower opinion on whether the information gathered might be used in an integrated pest management program. Questions were standardized and mailed to the growers before the interview took place and responses recorded in person at the interview (Table 1).

2.6. Statistical analyses

The data collected for this study were primarily from field surveys and not replicated experiments and therefore collected to describe and detect differences in mean estimators. Statistical analyses presented are therefore either Students t tests or single factor analysis of variance where appropriate and we used a conservative p value of 0.1 to determine significance. Least squares linear regression models were used to examine relationships including that between oyster survival and burrowing shrimp density in the injury threshold experiments.

3. Results

3.1. Program efficacy

Efficacy of the carbaryl treatment program on the beds we monitored was high, with an average reduction in burrow counts of 84% (n=11, SD, ±14%) in 1999 and 96% (n=7, SD, ±3%) in 2000 (Fig. 2). Lower efficacy in 1999 was due in part to results from a single bed (tract 231) where initial reduction in shrimp appeared to be only about 50%. Shrimp burrow counts represented a repeatable but highly variable index of shrimp abundance when observers were trained. We found that the standard deviation (SD) was related to the mean burrow count $\overline{X}$ for the beds we evaluated before carbaryl treatment (Regression, SD=2.35+0.5190, r^2=0.825, n=35). This results in a minimum detectable difference which also fluctuates with the mean (from 3.8 for a mean of 5 burrows m^{-2} to 25.6 for a mean of 60 burrows m^{-2}). There was potential for more observer error and variability associated with burrow count than with other variables we measured like shell cover, since burrows produced by other benthic invertebrates (primarily polychaetes and clams) often resemble those made by shrimp. This resulted in significant differences in burrow counts made by two observers (one experienced and one just trained) within the same quadrats

Table 1
Grower interview questions

Category	Questions
Background	Describe location, tidal height, area, and give brief bed ownership history.
Bed management	Describe culture type (ground, long-line, rack and bag).
	Is this a fattening or seed bed?
	Do you plant singles or cultch, triploids or diploids?
	How good is growth (good, average, bad) and why?
	Give the planting and harvest history (last 2 times planted, harvested).
	Is the bed handpicked or dredge harvested?
	Levels of planting/harvest (bags of seed planted, bushels of oysters harvested)?
	Was there any perceived or recorded loss to shrimp?
	Are there fallow periods when the bed is not used and is the bed harrowed?
	Has the bed been treated for shrimp before and when?
Bed ecology	Does the bed contain eelgrass and is eelgrass expanding or declining?
	Does the bed contain shrimp? If so, which species and are they expanding or declining?
	Are shrimp a persistent problem at this location?
Economics	How important is this bed relative to others you own?
	Could you afford not to use it?
	How many beds/acres do you own or lease and how many are in active production?
	Is this ratio of active/inactive beds stable over time?
	Describe how you utilize the shrimp information provided in the current burrowing shrimp management program and whether an enhanced program would benefit you.

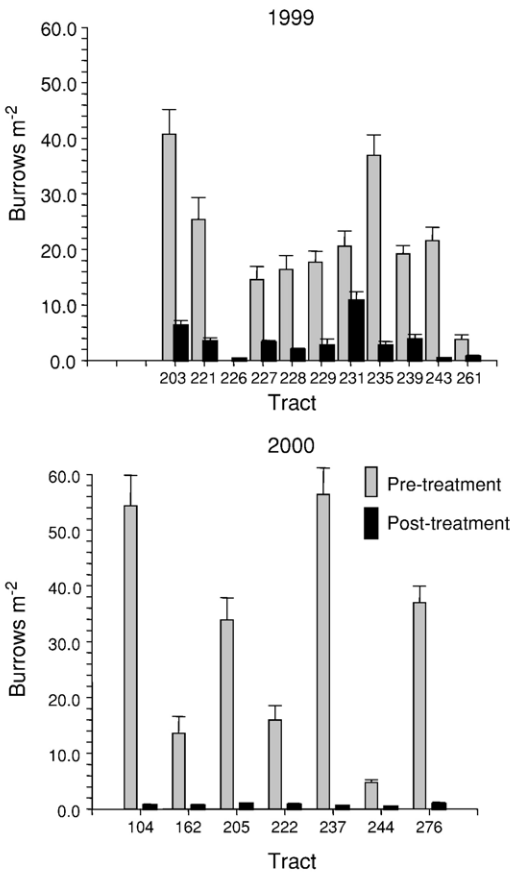

Fig. 2. Efficacy of carbaryl treatments made in 1999 and 2000. Burrow counts from transects on each tract before treatment (light bar) and 30 days post-treatment (dark bar). Error bars represent ±1 SE.

($n=10$ counts per observer, Students t test, $p=0.008$, Fig. 3 top), and consistent observer differences in separate counts made on this tract by these same observers (3 transects, each $n=10$, ANOVA $p<0.001$, Fig. 3 bottom), though significant differences were not observed among transects (i.e within observer, $p=0.15$).

3.2. Long term monitoring of shrimp/oyster dynamics

Data collected from beds over a representative 3 year grow-out cycle for oysters indicated that shrimp populations remained low for at least 2 years following treatment (e.g.,<10 burrows m^{-2} except for tract 231 with variable counts and less initial reduction noted above), and in some cases for the entire 3 or 4 year period (Fig. 4). Of interest were three tracts that were treated twice during the 5 year period of this study (Tracts 102, 203, and 227). Though the second treatment with carbaryl again significantly reduced shrimp burrow counts (ANOVA $p<0.001$, Table 2), in no case were the counts we measured before this second treatment above the prescribed regulatory level of 10 burrows m^{-2} or indicative of a significant shrimp re-infestation (mean counts ranged from 6–8 burrows m^{-2}). Subsequent Tukey multiple comparison tests indicated no detectable difference between post-treatment counts and those from the subsequent year, or even the previous year in one case (Tract 203, Table 2).

Burrow count estimates made by the consultant conducting pre-treatment assessments for the growers were significantly higher than those we measured for these 3 re-treated beds (>10 burrows m^{-2}, Students t tests $p=0.078$, $p<0.001$, $p<0.001$). Subsequent sampling on one of these beds (Tract 102) in 2000 indicated high densities of large clams were present ($\bar{X}=19.8$ clam burrows m^{-2} which were sampled directly and found to be *Macoma nasuta*). Our counts were often lower than those made by the consultant. Though this was not consistent for beds treated in 2000 (6 of 9 beds, Fig. 5), we accompanied the consultant on several pre-treatment

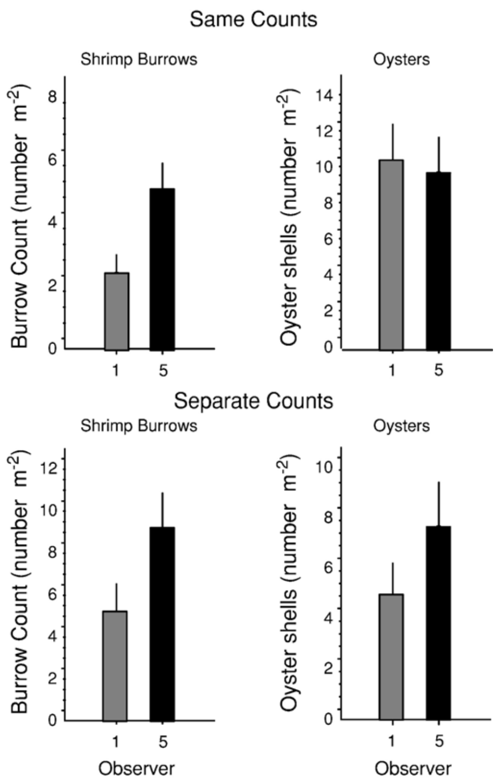

Fig. 3. Counts of shrimp burrows and oysters made by two separate observers on the same transect within the same quadrat on the same bed (top) and on separate quadrats placed along separate transects on the same bed (bottom). Error bars represent ±1 SE. Note the higher count of both oysters and shrimp by observer 5 when counting alone (bottom) and the similarity and therefore reproducibility of oyster counts, but not burrow counts (top).

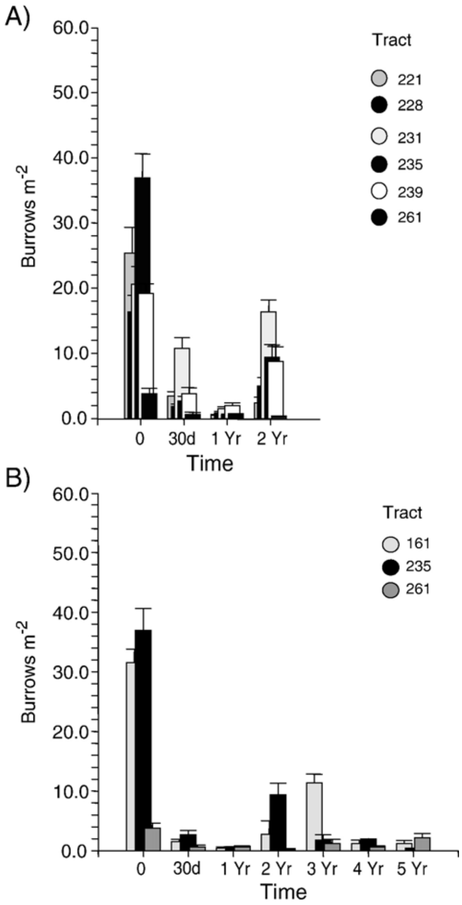

Fig. 4. A) Shrimp burrow counts measured on several tracts before and up to 2 years following carbaryl application. B) Shrimp burrow counts measured on tracts before and up to 5 years following application. Error bars represent ±1 SE.

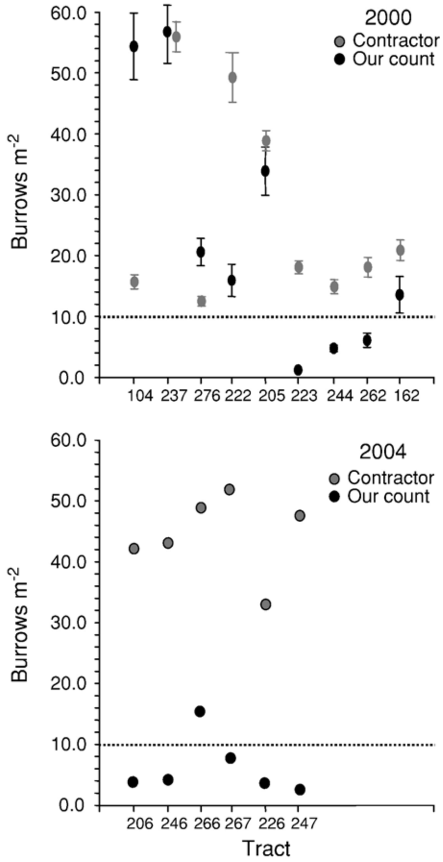

Fig. 5. Comparison of average shrimp burrow counts observed by the contractor and those we observed at several tracts before carbaryl application in 2000 (top) and 2004 (bottom). Error bars for 2000 represent ±1 SE, but original data were not available for 2004. Dashed line represents current regulatory threshold for treatment (10 burrows m^{-2}).

assessments in 2004 and found that in most cases the consultant appeared to be counting all burrows resulting in consistently higher counts, especially for those cases where we noted the presence of clams or polychaetes (Fig. 5).

Oysters were planted as seed on most of the tracts and then either grown to harvest size or moved as 2 year old animals to a harvest bed. Seed can be counted as individual pieces of cultch (oyster shell with multiple small individual oysters on each piece), but once the individual oysters on the cultch grow to a larger size, they must be counted as clusters or as new individuals, making it difficult to track survival of oysters on these commercial tracts across the entire grow-out period without tagging individuals. In general there appeared to be seed loss over at least the first year (range 10–40 seed or cultch m^{-2} at planting, 0 = 15 seed m^{-2}, declining to $\bar{X} = 10.5$ seed m^{-2}) and then a general increase in count as the oysters formed clusters became larger and split apart from the cultch ($\bar{X} = 22.5$ oyster clusters m^{-2} in year 2, Fig. 6). Percent shell cover can also be consistently measured and is correlated with seed loss (see Results under threshold experiment below) and later with oyster growth (Regression, r^2 ranged from 0.74 to 0.96 for 2 year old oysters on tracts displayed in Fig. 6). While oyster seed was planted at a smaller size on the two beds

Table 2
Results of ANOVA and Tukey multiple comparison tests on burrow count estimates taken before a second carbaryl treatment (Pre), after treatment (Post), 1 year before treatment, and 1 year following treatment for 3 tracts in the given years

Tract	*df*	*F*	p	Tukey
102	3	20.58	<0.001	2000Post 2001 1999 2000Pre
227	3	23.95	<0.001	2003 2002Post 2001 2002Pre
203	3	15.69	<0.001	2004 2003Post 2002 2003Pre

Separate treatment differences are underlined and Tukey results are presented in order with highest mean value on the right.

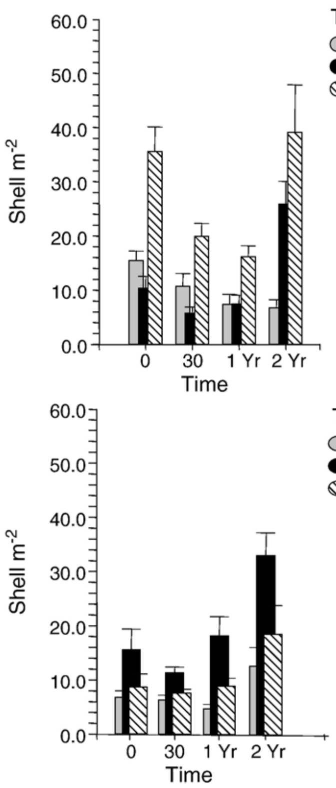

Fig. 6. Oyster counts on several tracts. Error bars represent ±1 SE. These were seed-harvest beds so numbers represent cultch for the first year and then clusters of oysters. They show either a slight decline over the first year or no change and then a general increase as the oysters grew and split apart from the cultch in year two.

monitored in Grays Harbor, growth was consistent with an increase in oyster count and percent shell cover that fit a linear curve with no difference between estuaries (shell area in $cm^2 = 3802^*$ age in yr – 3206; Students t test on slopes for two estuaries, $p > 0.50$).

Eelgrass (*Zostera marina*) was only consistently present on some beds where it increased in abundance until harvest operations occurred then declined, oyster seed was re-planted and the process began again (Fig. 7). Macro-algal cover (mostly *Ulva* spp. and *Enteromorpha* spp.) was related to shell cover, increased as shell cover increased (Fig. 8), and reached substantially higher levels on tracts in Grays Harbor (60–80% cover) than Willapa Bay (20–40% cover). Algal cover declined with oyster harvest and the process began again as it did for eelgrass.

3.3. Burrowing shrimp population monitoring

Recruitment of both species of shrimp at long term monitoring sites in Willapa Bay was relatively low during the period of this study (1999–2003) compared to previous years (Fig. 9; Dumbauld et al. 2004). Shrimp recruitment to oyster beds was also low with recruits found on only 3 tracts in 2000 (Table 3). Data from shrimp colonies measured at the same point in time in both estuaries (North and South Bay in Grays Harbor and Cedar and Palix River locations in Willapa Bay) was higher, but followed a similar trend with lower density in 2001 (Table 3). Samples taken in spring 2002 and 2003 at these control locations had no shrimp recruits in them (except one individual at Cedar River in 2002), so oyster beds were not sampled those years. Samples of larger shrimp taken using the 40 cm diameter core showed skewed length frequency distributions with >15 mm ghost shrimp and >25 mm mud shrimp representing much larger proportions (80% and 51% respectively) of the animals in 2001 than they did in 1995 when shrimp were recruiting in large numbers annually to these populations (Fig. 10). This trend was also evident in the distribution of average pre-treatment burrow counts observed by the consultant with more high counts in 1994 (when recruitment was regularly occurring) than during the period of this study in 2003 with a skewed distribution and more low counts (Fig. 11, data provided in unpublished annual reports to WDFW and WDOE).

3.4. Injury threshold experiments

Over 95% of the oyster seed had disappeared below the sediment surface within 28 days after placement in small fenced plots located in an area of very high shrimp burrow density (90–130 burrows m^{-2}, Fig. 12A). These high burrow density plots were abandoned after June.

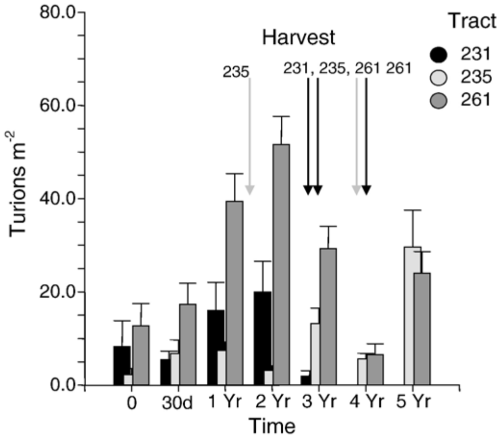

Fig. 7. Eelgrass density (measured as stem or turion counts m^{-2}) on several tracts where it was moderately abundant. Error bars represent ±1 SE. Note the general increase in density over time on each bed until a harvest operation (represented by arrows) which caused a decline.

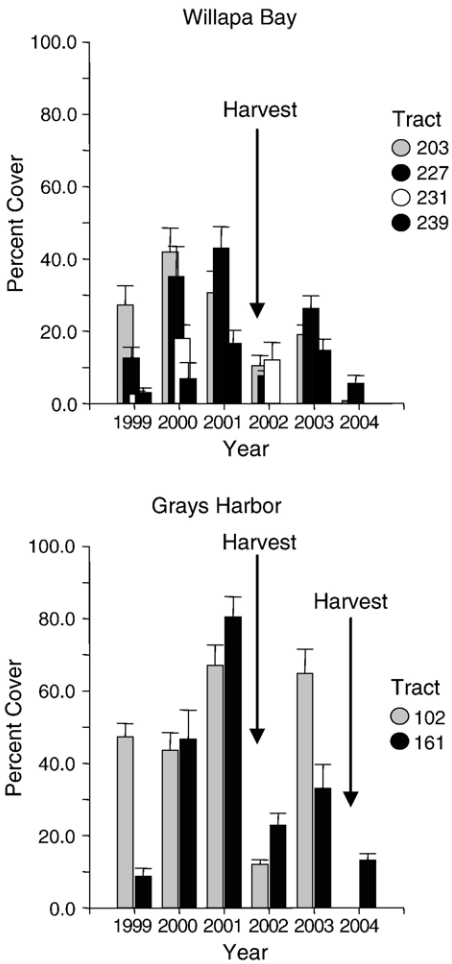

Fig. 8. Macro-algal cover on tracts in Willapa Bay (top) and Grays Harbor (bottom). Error bars represent ±1 SE. Algal cover followed the presence and growth of oyster cover as attachment sites, increasing from 1999 to 2001, after which oysters were harvested and the cycle repeats. Cover also varied from bed to bed with highest cover being observed on beds in Grays Harbor.

Oyster seed survival was greater over longer intervals in plots of moderate burrow density but survivorship varied among plots. An average of 69% of oyster seed in plots with burrow densities of 20–35 burrows m^{-2} disappeared within 42 days but seed density remained relatively stable for the rest of the summer on these plots (Fig. 12B).

Results of experiments conducted in areas of slightly lower shrimp density in 2003 were highly variable with high densities of polychaetes confounding burrow counts. Multiple regression analysis reflected the seemingly random affects of burrow density on oyster survival. Although a general linear model was significant ($df=62$; $F=54.894$), the small positive coefficient in the resulting equation suggests that oyster survival did not decline with increasing burrow density ($OS=13.56+0.03B-0.1D+0.07F$, where B is burrow density, D is number days since oyster placement, and F is presence or absence of fence; adjusted $R^2=0.71$, SE=1.87).

Both fattening and seed oysters increased in size in the large plot experiments. As noted above, seed can be counted as individual pieces of cultch (shell with multiple small individual oysters on each piece), or as individual oysters as they grow. While absolute abundance of either cultch or oysters is an important measure of yield, it was closely correlated to percent shell cover ($R^2=0.87$, SE=1.40, $N=20$), which provided a more consistent and standardized unit of measurement in these plots. Changes in oyster density relative to shrimp burrow density were even more apparent when percent shell cover was normalized to maximum cover in each treatment (percent shell cover divided by maximum percent cover sampled within each treatment combination) allowing stronger within treatment comparisons. As expected, both seed and fattening oysters survived longer in sprayed plots compared to unsprayed plots (Fig. 13). Seed density and shell cover declined to near zero within 8 months of planting on the unsprayed plots. Burrow densities were higher in the unsprayed plots ($\bar{X}=9.6 \mp 13.9$ burrows m^{-2} vs 0.8 ∓ 1.2 burrows m^{-2} in the sprayed plots), especially during the warm summer months when shrimp were most active, but the average at the end of the observation period was very similar to that at the outset of the experiment. Burrow density was low in the sprayed plots when oysters were planted

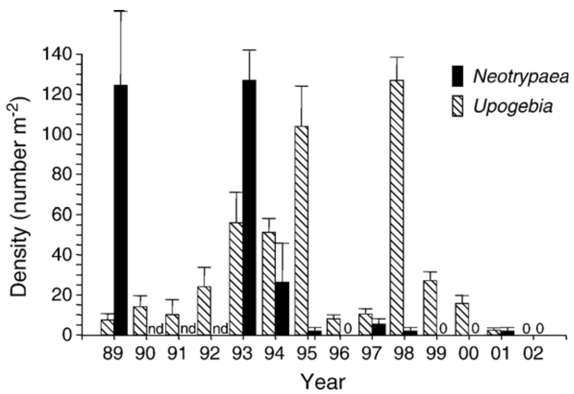

Fig. 9. Shrimp recruitment patterns at long term monitoring locations. Solid bars represent the annual pattern for ghost shrimp collected with a small core from a dense shrimp colony in Willapa Bay with strong recruitment shown for 1989, 1993 and 1994, especially compared to years of this study (nd=no data collected). Shaded bars represent values for 0+mud shrimp sampled in a similar colony with a larger core and separated by size class. Strong recruitment for this species occurred in very different years (1995 and 1998). Error bars represent ±1 SE. Graph modified from Dumbauld et al. (2004).

Table 3
Average number of small recruits (<1 year old shrimp, *Neotrypaea californiensis*) found in samples taken on oyster tracts in 2000 and 2001 using a small 26.5 cm dia. core (*n* = sample size, SD = standard deviation)

Location	Tract	Month/Year	n	Mean density (#/m^2)	SD
Grays Harbor	102	7/2000	7	0	0
		5/2001	10	0	0
	161	5/2000	8	0	0
		8/2000	5	3.6	8.0
		5/2001	10	0	0
	N. Bay	4/2000	10	5.4	8.7
		5/2001	10	9.0	13.7
	S. Bay	4/2000	10	14.5	22.2
		5/2001	10	10.8	12.5
Willapa Bay	203	5/2000	10	0	0
		8/2000	10	0	0
		4/2001	10	0	0
	221	5/2000	7	0	0
		8/2000	10	0	0
	227	4/2000	10	1.8	5.7
		8/2000	10	0	0
		4/2001	10	0	0
	228	8/2000	6	0	0
	231	4/2000	10	0	0
		4/2001	10	0	0
	235	4/2000	6	0	0
		8/2000	10	1.8	5.7
		4/2001	6	0	0
	239	8/2000	10	0	0
	261	4/2000	10	0	0
		7/2000	10	0	0
		4/2001	10	0	0
	Cedar	4/2000	10	10.8	15.2
		4/2001	10	1.8	5.7
	Palix	5/2000	10	18.0	22.4
		4/2001	10	1.8	5.7

Also shown are recruit densities found at control locations (no recent history of oyster culture) in dense shrimp colonies during the same years (N. Bay and S. Bay in Grays Harbor, and Cedar and Palix Rivers in Willapa Bay).

($\bar{X}=0.5 \mp 0.6$ burrows m^{-2}), and increased only slightly over the 20 month observation period, most likely due to immigration by adult shrimp. Densities of both fattening and seed oysters dropped sharply during the first winter after planting, even at low burrow densities, demonstrating the importance of seasonal events unrelated to shrimp density. A relationship between oyster yield, burrow density, and time was evident, but a threshold was not discernible.

3.5. Grower interviews

We interviewed 6 growers who together owned approximately 12,300 acres and actively farmed about 4900 acres of tidelands in Willapa Bay and Grays Harbor. These farms ranged in size from 190 acres to 7110 acres. The beds we monitored were currently being used for ground culture and most were either seed beds where seed was planted and then moved elsewhere after 2–3 years or seed-harvest beds where seed was planted and oysters left to grow and fatten through harvest. Most growers reported good growth and attributed this to either specific conditions like tidal elevation or proximity to channels or to the recent good ocean conditions. Eight of the twelve beds were harvested with an oyster dredge, the rest were picked by hand harvest. Most of the beds were also harrowed with a pasture harrow at some point during the growth cycle to bring oysters up to the surface and/or break up oyster clusters. All of the beds had been previously treated with carbaryl. Growers reported that most of these beds were treated regularly on a 3–4 year cycle although at least one bed had not been treated for a decade. The growers reported that shrimp were a consistent problem with only one bed being reported as receiving just moderate re-infestation. Eelgrass was reported present on all of the beds, but was clearly more common on some. All but one of the growers answered that they could not afford to leave these beds fallow for even a single season. One grower felt he might be able to do so if market conditions changed. Interestingly, most growers reported that they did not pay close attention to the shrimp burrow count information provided as part of the pesticide application program, and were most concerned with whether the minimum level of 10 burrows m^{-2} required for permitting was achieved, so treatment could occur.

4. Discussion

Aquacultural pest management programs are in their infancy compared to long established counterparts in terrestrial agriculture. Most are targeted at invasive species like the introduced mussel *Mytilopsis* in Australia (Bax, 1999) and especially exotic algae and plants like the marine alga *Caulerpa* and salt marsh invader *Spartina* (Williams and Schroeder, 2004; Major et al., 2003; Moreira et al., 1999). Thalassinid shrimp are a problem in penaeid shrimp aquaculture in Columbia, South America (Nates and Felder, 1998; LeMaitre and Rodrigues, 1991), but are relatively easy to control by temporarily draining the ponds and/or using a pesticide once the pond is drained. The burrowing shrimp management program under scrutiny here features a native crustacean in an open estuarine system and is unique in the world.

Integrated pest management (IPM) has a 30 year history and has been widely applied in terrestrial agriculture with numerous success stories (Kogan, 1998), yet

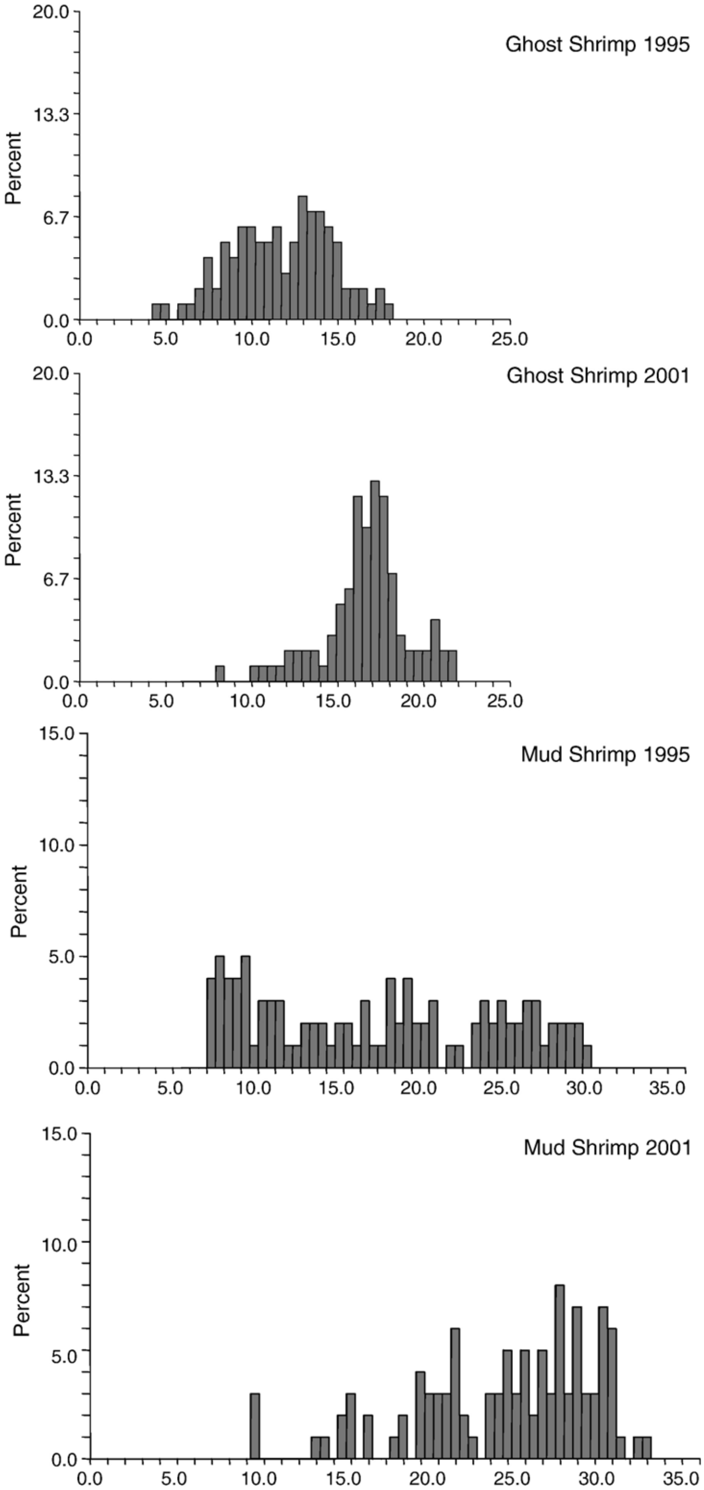

Fig. 10. Length frequency diagrams for populations of both species of shrimp at long term monitoring locations comparing 1995 data, when shrimp were recruiting regularly, to that collected in 2001 during this study when recruitment was low. Note the scarcity of small individuals and right skewed age distributions observed in 2001.

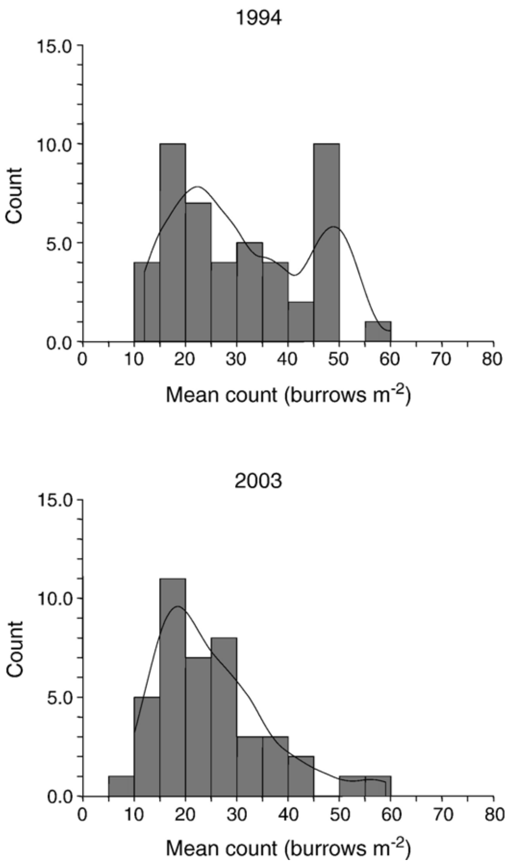

Fig. 11. Frequency distribution of average burrow count measurements made by contractor on treatment tracts in 1994 (top) and during this study in 2003 (bottom). Note greater frequency of counts above 40 burrows m^{-2} in 1994 and generally skewed distribution in 2003 with most counts below 30 burrows m^{-2}. Data from unpublished annual reports to WDFW and WDOE.

has been infrequently applied in marine aquaculture (see Rae, 2002 for use in salmon culture and numerous references for use in rice culture e.g. Halwart, 2003). Parallels suggest that IPM could be applicable to burrowing shrimp management in oyster aquaculture (beds of cultured oysters resemble agricultural fields and shrimp have complex life histories like many insect pests), however the physical environment (tidal flow in an estuarine system), ecology of the pests (shrimp are relatively long lived and burrows extend to 60 cm deep in the intertidal sand and mud), and regulatory climate/political differences (pesticides are not generally applied to estuaries and in fact use is regulated to prevent aquatic system exposure), make establishing such a program a unique challenge. Because the pesticide carbaryl is the only tool that has been broadly used to control these shrimp to date, the existing pest management program cannot be considered to be integrated. Our goal in this study was to develop some of the tools necessary to fit the definition of Level 1 integration: an accurate monitoring program with field scouting of pests and threshold levels for treatment and inaction (Kogan, 1998). These tools will be essential whether or not alternatives to carbaryl are found. Such alternatives include the selective management of indigenous natural enemies, augmentative biocontrol, physical methods, or other chemicals that enable different levels of integration to be achieved.

Although program efficacy had previously been examined using small scale experimental plots to define appropriate application rates (Dumbauld et al., 1997; WDFW and WDOE, 1992), long term monitoring of routine large scale field applications had not been conducted. We found that aerial applications of carbaryl at 9 kg a.i. (active ingredient) per ha (8 lb per acre) were highly effective against thalassinid shrimp on these shellfish growers beds, resulting in immediate (85–95%) and long-lasting decreases in shrimp burrow density. We also found that although burrow counts are the only practical measure of shrimp density on the scale necessary for this treatment program, they are subject to observer error and are both temporally and spatially variable due to shrimp population dynamics and environmental conditions as has previously been shown for these species and other thalassinids (Dumbauld et al., 1996; McPhee and Skilleter, 2002). Measurements should be made as close as possible to treatment periods and/or during summer months when shrimp are active and recent storm activity low (Dumbauld et al., 1996). It may be possible to take these measurements a season in advance (the previous summer) as long as shrimp recruitment is concurrently being monitored as we recommend (see discussion below). Observers must be trained to recognize and distinguish shrimp from polychaete and clam burrows, and we recommend occasional small cores be taken when identity is uncertain, however some errors seem inevitable especially when burrow counts are low (<30 m^{-2}).

The long term impact of the treatment program was somewhat more difficult to discern given the relatively low recruitment of shrimp post-larvae to these estuaries during the study period (1999–2003). Most oyster beds treated during the first year of the study remained relatively free of shrimp for the entire study period, which encapsulated at least one and sometimes two oyster crop cycles. The planting and harvest cycle for oysters themselves had the greatest impact on algae and eelgrass present, with harvest operations clearly impacting both of these variables when present and the presence of algae being correlated to the presence of shellfish, probably as attachment sites. Because these shrimp have pelagic

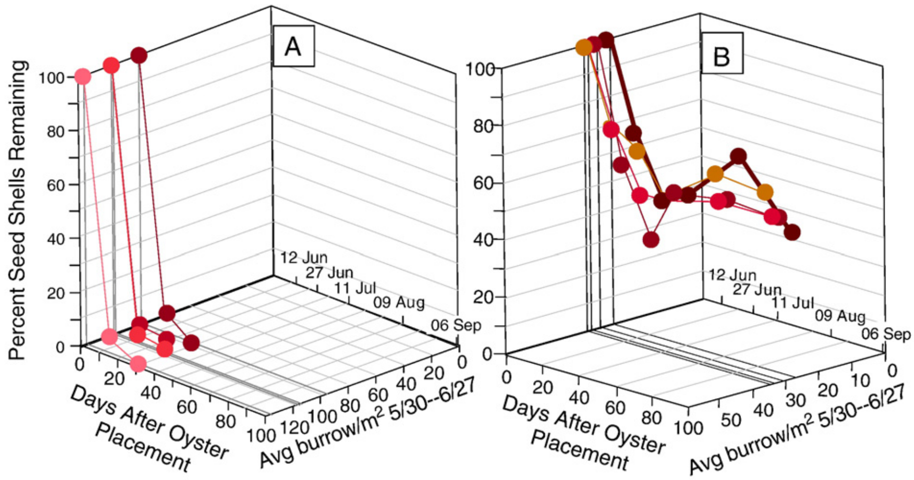

Fig. 12. Mean oyster seed survival on plots with A) high (90–130 burrows m^{-2}) and B) moderate (20–35 burrows m^{-2}) densities of burrowing shrimp over time at Cedar River location.

larval stages that are flushed from the coastal estuaries into the nearshore coastal ocean (Pimentel, 1983; Johnson and Gonor, 1982), annual recruitment to oyster beds is driven by nearshore coastal oceanography and the success of post-larval shrimp returning to the estuaries. The long term record we establish here suggests that recruitment for

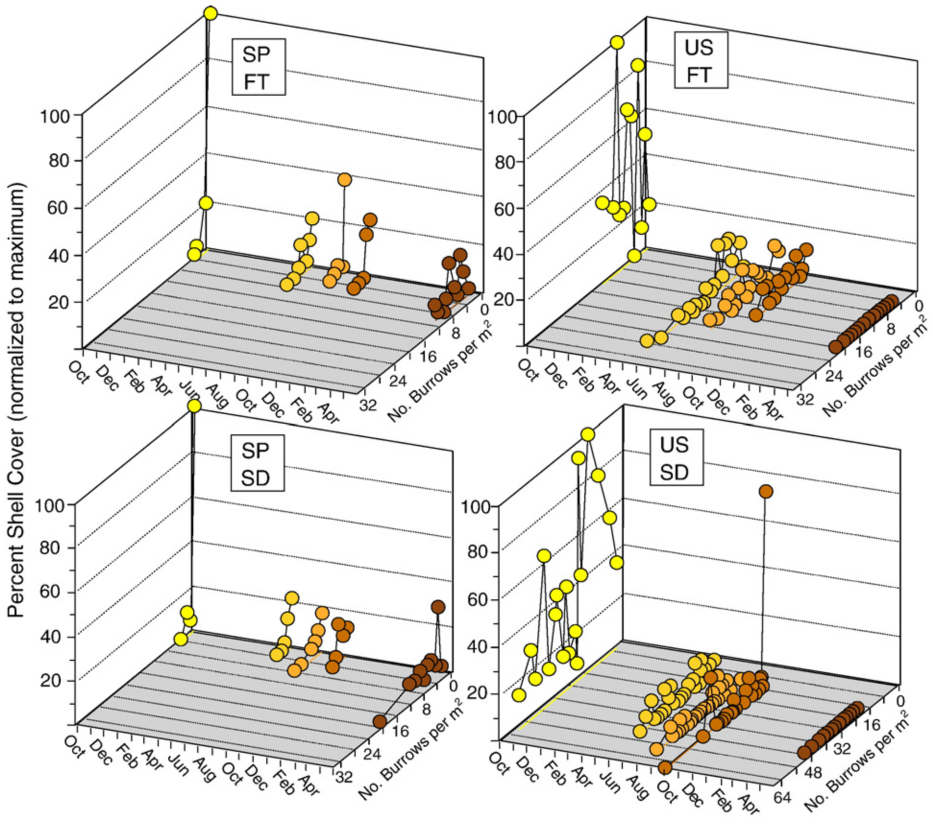

Fig. 13. Oyster density (normalized percent cover) of fattening (FT) or seed (SD) oysters on large plots either sprayed with carbaryl (SP) or left unsprayed (US) at each measured burrow density. Percent shell cover was averaged at each sample date for each burrow density count; thus each point may represent multiple counts at the same burrow density.

both species of shrimp was greater and more regular during the early 1990's than during the period of this study. This confirms observations by the growers and others (Dumbauld et al., 2001; Feldman et al., 2000) that shrimp recruited immediately back into treated beds during those years and shrimp burrows appeared to be just as abundant 1 year after pesticide application as before the pesticide was applied. This is also loosely confirmed by the reduced frequency of high (>30 burrows m^{-2}) counts observed on treated beds in 2003 compared to 1994 and the skewed age distribution of larger shrimp now present at these reference monitoring sites (Figs. 10 and 11), although the latter could also be explained by exceptional growth in recent years or movement of larger shrimp from place to place. The long term recruitment data demonstrate that the two species of shrimp display different recruitment patterns. This is likely due to the timing of reproductive activity, when larvae are present in the water column, and differences in coastal currents (mud shrimp recruit during late spring/early summer while ghost shrimp recruit in late summer/early fall; Feldman et al., 2000; Dumbauld et al., 1996; Johnson and Gonor, 1982). Although recruitment was low during this study, we argue that developing a technique to hind-cast shrimp recruitment using oceanographic information collected during the previous year's larval period or continuing to monitor shrimp recruitment to the benthos just prior to implementing control will be an important aspect of an integrated pest management plan for these shrimp.

Integrated pest management programs traditionally use economic injury level (EIL) and economic action threshold (ET) models to establish objective criteria for when and where control tactics are used (Pedigo, 2002). Pest control is not warranted until pest densities measured in the field reach thresholds established in these models. Pest control is usually expected to be implemented at the ET before losses are incurred from reaching the EIL. Estimating the ET value is complex because it is based on the growth rate of the pest population and so requires estimates of how the pest population changes over time and further, in the case of a perennial crop like oysters, how the size, age and density of the crop itself responds over time. Thus for burrowing shrimp in commercial oysters, a plant or crop-based threshold like that developed for cotton (Mi et al., 1998) may be more appropriate than a pest-based threshold. Finally, the ET is often based on a linear damage density function but in fact this function is likely to be non-linear due to seasonal relationships in physical and other biological factors affecting the population.

Our experimental work clearly showed that moderate to high densities of ghost shrimp (*N. californiensis*) cause significant oyster mortality as has been previously demonstrated (Dumbauld et al., 1997). We did not conduct experiments in areas where mud shrimp (*U. pugettensis*) were the dominant species present, but expect that this species would have less impact based on previous work (Dumbauld et al., 2004). It was evident that there was some type of non-linear function occurring with losses increasing substantially between 20 and 40 burrows m^{-2}, but we were unable to further define a true threshold function, especially one that growers would be able to practically use to decide when they should initiate treatment. While this was in part due to experimental conditions (issues with scale, difficulty counting shrimp burrows, and artificial conditions introduced with fencing around small plots), it may be very difficult to refine this function further, given the multitude of variables influencing oyster loss and shrimp abundance over the multi-year period before the crop is harvested. For example, had shrimp recruitment been higher, this too would have affected the relationship in a non-linear fashion over time. Additional factors including variability in market price for oysters and difficulty predicting environmental values (both positive values for decreasing pesticide impacts and potentially enhancing habitat and negative values for remaining pesticide impacts) would make developing a true EIL even more difficult (DeWitt et al., 1997).

Some of the difficulties in developing ET's and EIL's have also been experienced by researchers in terrestrial agriculture. Successful efforts where these concepts have developed into integrated pest management programs tend to involve simpler damage density functions where crop damage occurs over a short time interval with more predictable patterns in both pest life history and crop development over time (Barigossi et al., 2003; Mendoza et al., 2001). The plant-based threshold developed for cotton, as mentioned above, utilizes a multi-stage model with several variables including crop structure, recovery, yield loss damage, maturity delay, and other crop specific indicators of development and data collected actively during the crop cycle to address the dynamic nature of the pest control decision (Mi et al., 1998). Unfortunately, both pest and crop development are much less well known for the oyster aquaculture system and may remain so due to several factors including practical issues such as restricted access to the beds by boat during spring and summer low tides, lack of detailed information regarding other factors affecting oyster growth such as phytoplankton availability and disease, and a somewhat volatile market and very restricted profit margin for the product.

This does not imply however that integrated pest management theory and practice cannot be successfully applied to burrowing shrimp in this marine aquaculture system. Our data demonstrate that monitoring shrimp recruitment and population dynamics within the estuarine system in addition to collecting data from shellfish beds is important, and that growers unnecessarily re-treated some beds during the period of our study. Depending on the culture method, type of bed, and vicinity to nearby shrimp colonies from which larger juvenile or adult shrimp might move (i.e. we assume little movement), it may only be necessary to predict relative shrimp abundance for 1 or 2 years in advance when deciding on whether to treat a bed because new recruits, due to their small size, will not affect oysters for at least 2 years. This would especially be true for transplant beds and seed beds where the oyster crop will only be present for one to 2 years, while the most problematic scenario is for seed-to-harvest beds or any bed where the crop is expected to be in place for a greater period of time and/or during periods when growth is slow or markets are flooded and oysters remain on beds for 3 years or more. Given the uncertainty in shrimp recruitment and population dynamics, the difficulty in distinguishing shrimp burrows and therefore inaccurate nature of burrow counts, and previous experience with regular patterns of recruitment during the early 1990's, a more preventative approach may be necessary for these situations. Although we observed uncertainty in burrow counting measures (mostly due to observer error, counts being relatively precise, ±about 6 burrows m^{-2}) and no precise threshold function, we suggest that burrow counts remain the only viable method for assessing shrimp abundance at the necessary spatial and temporal scales. The current regulatory threshold of 10 burrows m^{-2} is conservative, but in conjunction with estimates of recruitment and improved counting measures, may serve as a reasonable guideline, since data suggest substantial losses occur somewhere between 20 and 40 burrows m^{-2} (for ghost shrimp; this being conservative and this density level probably higher for mud shrimp). If recruitment is predicted to be low and particularly if it was low the previous year, we therefore recommend treatment only occurring on those beds where the average burrow count exceeds a slightly higher threshold of 20 burrows m^{-2} based on our long term data (Fig. 4). If however, annual recruitment has been occurring regularly, then treatment might be prudent when the level exceeds 10 burrows m^{-2}, and the fact that small shrimp burrows are not assessed with our method. This is formulated into a simple decision tree which we suggest be used as an empirical EIL (Fig. 14) that could be implemented regardless of the control measure being used.

Based on the oyster growers' responses to our interview questions, the greatest challenge may be convincing the industry to adopt the monitoring plan as part of the larger integrated pest management effort, and especially to convince growers not to treat beds that are their prime growing areas which they cannot afford to lose to shrimp. This will be especially true given their experiences with loss during years such as the early 1990's when shrimp were regularly recruiting back to treated beds (Fig. 9). The growers are currently mandated through a National Pollutant Discharge Elimination System (NPDES) permit to contract for an assessment program in order to use the pesticide carbaryl. However, they don't rely solely on this information to decide when to treat. A comparison of the data collected by ourselves and the contractor prior to the 2004 treatment program

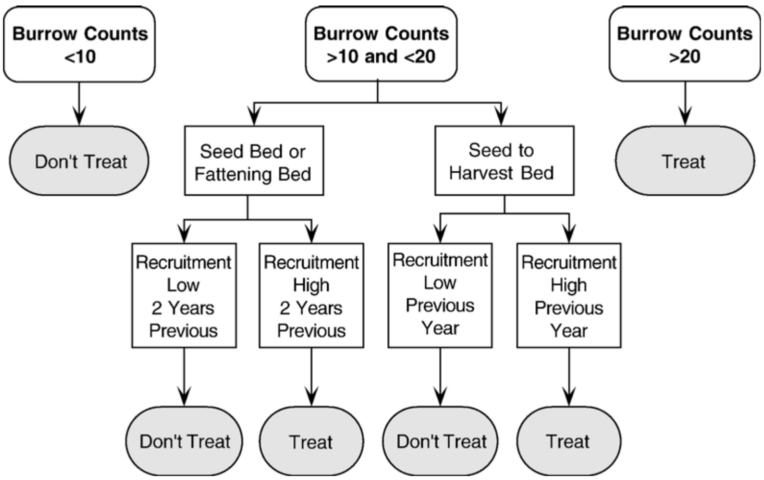

Fig. 14. Diagram of a suggested empirical decision tree to be used as a tool for deciding whether to treat an oyster bed based on the type of bed and a consistent monitoring program which examines both the density of shrimp on the oyster bed and recent trends in shrimp recruitment.

suggests that few of the beds chosen would have been recommended for treatment during this year based on our decision tree (38 of the 39 beds based on the contractors burrow counts, but none of the six beds we sub-sampled based on our counts, Fig. 5). Nonetheless, integrated pest management remains a desirable (and mandated) goal for controlling burrowing shrimp populations. Level 1 integration (monitoring and threshold levels for inaction) seems achievable with the tools we present here. In addition, applications of integrated pest management measures modeled after the burrowing shrimp example should prove valuable for the control of other pests, predators and diseases affecting commercial fisheries and aquaculture resources.

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